UTILIZING SIMULATIONS FOR PERFORMING DEGRADATION TREND ANALYSES

1993

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ABSTRACT

The process of modifying a simulations model for supporting stockpile reliability program (SRP) analyses of a tactical missile system is described. Basic application of the modified simulation to SRP analyses is discussed. A methodology for supporting degradation trend analyses by predicting future performance is developed. Examples from an ongoing analysis are provided. It is shown that this is a valuable tool with significant growth potential. Model programming and system design considerations that should be incorporated early in program development in order to optimize future applications of the methodology are discussed.

INTRODUCTION

Missile systems are originally procured with a predicted shelf life. After fielding, system data is analyzed to assess the original shelf life prediction and perform shelf life extensions whenever possible and necessary. This Army program is referred to as the Stockpile Reliability Program (SRP). Historically, Army missile systems have been procured with an average seven-year shelf life, however, through the SRP the shelf life has been extended to an average of 18 years. SRP utilizes a variety of test methodologies and analysis techniques customized to each missile system. In general, data is collected over the life of the missile system from surveillance (field storage and operations), flight testing, and disassembly/component testing. This data is then analyzed for trends associated with age, manufacturing strata, and exposure environments. Undesirable trends may result in suspension, restriction, or risk acceptance. When the system continues to perform reliably and safely, and still meets a tactical need (i.e., is not obsolete, or replaced by a new system), then a shelf life extension will be coordinated with the Army missile community. For obvious reasons this program attains high visibility. For example, extending a system's shelf life may have a significant impact on the decision to procure a replacement system. Shelf life extensions must be taken seriously, with the greatest possible statistical confidence imposed. Unfortunately, due to significant operating budget shortfalls, the Army SRP is extremely constrained. Accordingly, several new initiatives have been undertaken in SRP to improve the confidence of the analyses at equivalent or reduced costs. One of these initiatives is to extend the use of simulation models created during system development for assessing and predicting missile system shelf life.

INTERNET DOCUMENT INFORMATION FORM

A . Report Title: Utilizing Simulations for Performing Degradation Trend Analysis

B. DATE Report Downloaded From the Internet 11/20/98

C. Report's Point of Contact: (Name, Organization, Address, Office Symbol, & Ph #):
U.S. Army Aviation & Missile Comm
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Redstone Arsenal, AL 35805

D. Currently Applicable Classification Level: Unclassified

E. Distribution Statement A: Approved for Public Release

F. The foregoing information was compiled and provided by:
DTIC-OCA, Initials: VM_ **Preparation Date:** 11/20/98__

The foregoing information should exactly correspond to the Title, Report Number, and the Date on the accompanying report document. If there are mismatches, or other questions, contact the above OCA Representative for resolution.

Specifically, this paper reflects efforts associated to the HELLFIRE SRP. The HELLFIRE SRP utilizes an annual sample of 15 HELLFIRE missiles for disassembly and component testing, and 21 missiles biennially for flight testing. In general, all of the samples are selected from dedicated assets. These are missiles that were sampled across production and set aside specifically for SRP testing. HELLFIRE model AGM-114A (PA79) and AGM-114C (PD68) missiles were sampled, starting in 1985, with a total of 487 dedicated assets assembled by 1989. These missiles were electronically all-up-round (AUR) tested and then placed in carport type structures in Alaska, Arizona, and Panama. These structures expose the missiles to the environment while not subjecting them to direct precipitation or solar loading. The missiles are maintained in their original shipping containers IAW the HELLFIRE Supply Bulletin (SB) 742-1425-92-010. The Army HELLFIRE SRP was designed to promote natural accelerated aging (within the specified storage limits) in order to project future stockpile performance by identifying trends in the dedicated assets prior to their occurrence in the stockpile. In addition, samples may be selected from the field for special tests. For example, a total of 48 missiles were sampled from the Operation Desert Storm retrograde. Twenty of these missiles have been flight tested, and 14 of these were disassembled and component tested.

After performing HELLFIRE SRP sample selection, the missiles are shipped to the Redstone Technical Test Center (RTTC), Redstone Arsenal, Alabama. The RTTC provides AUR testing, X-ray, disassembly, and component functional testing. Propellant samples are provided for chemical and mechanical analyses. Missiles selected for flight testing are provided to Eglin Air Force Base after the completion of AUR testing and X-ray at RTTC.

A total of 206 SRP missiles have been tested since 1990, with 120 missiles being component tested and 86 being flight tested. It should be noted that there are additional sources of data that are monitored for trends, e.g., malfunction reports, ammunition condition reports, quality deficiency reports, etc. Additionally, surveillance vans perform non-destructive electronic testing of the dedicated assets and other samples from the inventory annually. The surveillance van measures 126 electronic parameters, and is the source of over 20,000 missile tests.

Until 1993 there was no capability to analyze the extensive amount of data that had been collected on the electronic components. These components have numerous performance parameters that can be tested at several environmental conditions without destroying the component, thereby producing a large amount of data. A high priority was placed on loading this data into a system that could be accessed, downloaded, and then analyzed using a desktop personal computer. This effort was completed in December 1993 and currently contains over three gigabits of SRP and surveillance data.

Generally, SRP analysis involves plotting parameter data versus age at the time of test, then performing curve fitting to identify parameters that display statistically significant trends. An example of this type of analysis is shown in figure 1. When a trend is identified, the reliability engineer is confronted with the task of determining what affect (if any) the trend will have on the missile system's reliability, safety or performance. This is often not an exact

science. Parameter specifications were often the result of engineering judgment to begin with, and the actual point of mission affecting failure could be at the specification limit, or far outside it. Additionally, the combined affect of multiple minor trends, for which the individual parameters approach the limits but do not exceed them, cannot be evaluated through this traditional trend analyses technique.

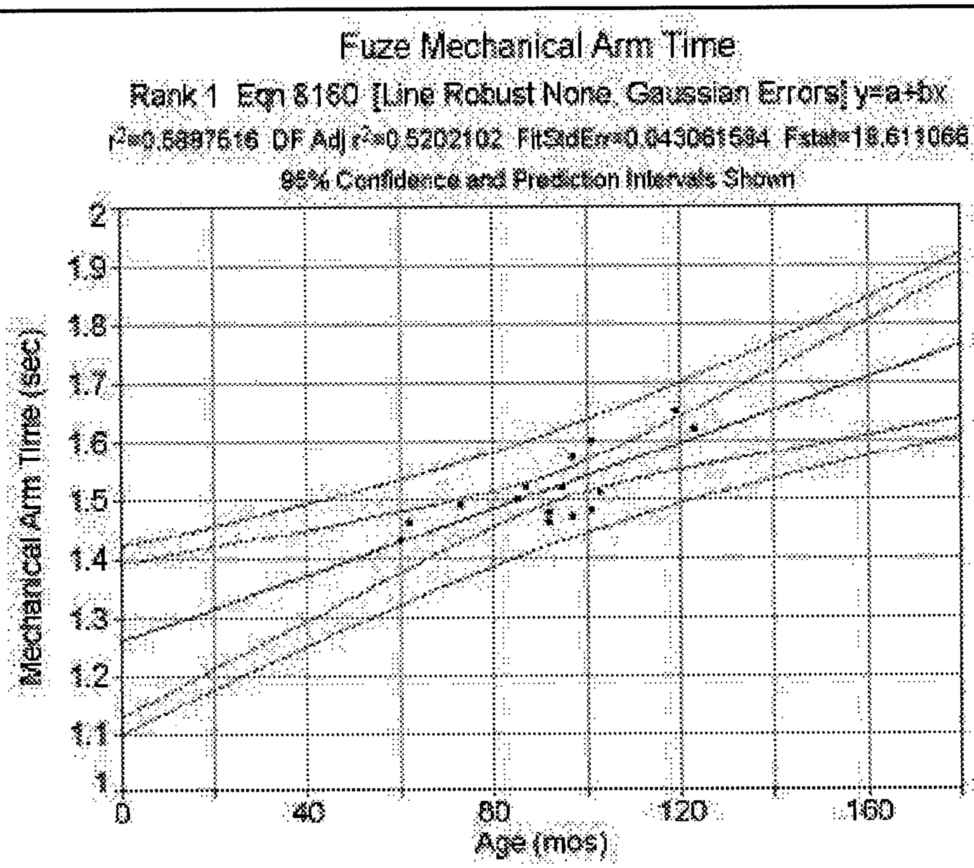


Figure 1. Example of traditional SRP trend analysis. (Note: Data not to be construed as actual)

MODIFICATION OF THE SIMULATIONS MODEL

A six-degree-of-freedom (6-DOF) simulations model known as the Laser Designator Weapon System Simulation (LDWSS) was originally developed to support development and production of the HELLFIRE missile. The LDWSS runs a multiple number of trials per scenario in a Monte Carlo fashion. It can output various plots such as trajectory and miss distance. The system calculates circular error probability and probability of hit.

After the electronic component SRP data was successfully transferred to database we identified the need to find a better method for analyzing the large amount of data. We also

became aware of it's significant potential for simulations applications. Based on consensual identification of this need, several agencies teamed to modify and validate the original LDWSS model for this application. The approach was to initially bring the simulations personnel together with the test personnel. The test personnel provided background information to the simulations personnel on all testing and parameter readings taken during SRP tests. With this information, the simulations personnel were able to identify which of the parameters could be applied directly to the existing LDWSS model, and which could be applied through minor modifications to the model. Then, in a team effort between system engineers, SRP analysts (reliability engineers), and simulations personnel, optimum areas for modification of the LDWSS model were selected. For example, if a modification could be made to allow entry of a specific parameter, but it was identified by the system engineer that the parameter would have insignificant impact on system performance, or it was determined by the SRP analyst that the parameter would be unlikely to change with age, that modification might not be performed in lieu of other more critical. Modifications were performed in the seeker, control section and autopilot models. Additionally, a simple model, which did not exist previously, was developed for the thermal battery and integrated with LDWSS.

In the process of this development, it was realized that the original means and distributions for the parameters used in the LDWSS were not necessarily reflective of the readings actually being measured in SRP testing of the inventory. This should not have been a surprise, since the means and distributions were based on the specification requirements, combined with engineering analyses of what distribution would be expected for each parameter. No known "follow-on" attempt to analyze data on actual production hardware in order to re-calculate means and distributions had ever been performed. Using the SRP database the simulations personnel developed more realistic means and distributions for all available parameters based on actual data collected on 0-4 year old missiles. This became a significant, yet initially unplanned modification to the simulations model. After reviewing the planned modifications with all members of the development team, the simulations personnel performed a validation-verification utilizing available flight test data. Effort was then shifted to the application of the model.

BASIC APPLICATION METHODOLOGY

When the exemplary work to modify the model was completed, the reliability engineer became involved in determining how the simulation would be applied. It was quickly apparent that the other personnel on the team had their own ideas of how to apply the model, and at that time, we had insufficient funding to further influence the effort. Emphasis was therefore placed on performing applications of interest to the systems engineers. These analyses would be the most likely to have an immediate impact on the ongoing production of follow-on models of the HELLFIRE missile.

Component testing of SRP assets has often identified failures of items for specific test parameters. The systems engineers believed that most of these "failures" would have little or no impact on system performance. In general, this became the basis for utilizing the simulation to "re-build" a missile from it's component test results. For example, even if a missile failed to meet a specification parameter, how would it have performed if actually flown? Therefore, the direction by the systems engineers was to "re-assemble" missiles from their component data, and "fly them" in the simulation. The next step was to identify appropriate flight test scenarios. Working with test engineering and a seeker technical expert, 20 flight scenarios that were believed to represent "edge of the envelope" performance were selected. These vary in range, offset angle, flight mode, and designation delay. For two years, all of the component data for each SRP missile sampled (15/yr, 30 total) was plugged in to the model to simulate how the missile would have performed if it had been flown at each of the 20 scenarios. It was decided through limited engineering analysis that 5000 run-sets for each scenario would be used. This was considered a large enough sample to support statistic statements. "Rebuilding missiles" in the simulation was not without merit. For example, one control section failure that previously was believed would not affect system flight, was identified to affect probability of hit under specific scenarios. Under previous methodologies, we would have concluded that this missile would not have been affected by the minor failure. Using the simulation, it was discovered that the missile would have had significant reductions in the probability of hit under some flight scenarios. Discovering this, even on only one of 30 missiles analyzed, was a significant advance in SRP analysis.

Recall the original objective of the SRP program, "to predict the <u>future</u> performance of missile systems". It is apparent that this re-building of missiles in the simulation has limited value for satisfying this need. However, we could now report something to the effect that "if these 15 missiles, ranging in age from x to y years were flown in this scenario, z% would have hit the target." This was an improvement. We could "fly" an SRP missile over-and-over under numerous scenarios after it had been re-created in the simulation, but it is clear that there is room for additional application methodologies.

DEGRADATION TREND ANALYSIS METHODOLOGY

Generally, most persons involved in the project only identified with the capability to calculate probability of hit for missiles of various ages. They felt that trend analyses could then be performed on the relationship between probability of hit versus age. Unfortunately this provides no significant improvement to SRP analyses. Based on the missiles being spread across various ages, combined with the fact that missiles could not be re-built in the simulation if one component experienced a hard failure, this methodology yielded a very small, loosely distributed sample set. An example of this methodology being applied is demonstrated in figure 2. These analyses exhibited very low statistical confidence. Additionally, it took no advantage of the extensive amount of test data collected on the inventory utilizing the surveillance van.

As stated previously, there are two significant shortfalls with the traditional method of SRP analysis based on individual parameter degradation trends. One is that it is often difficult to determine the point at which a trend will affect the missile mission. The other is that it is impossible to evaluate when a combination of minor trends will affect the missile mission. We needed to develop a new

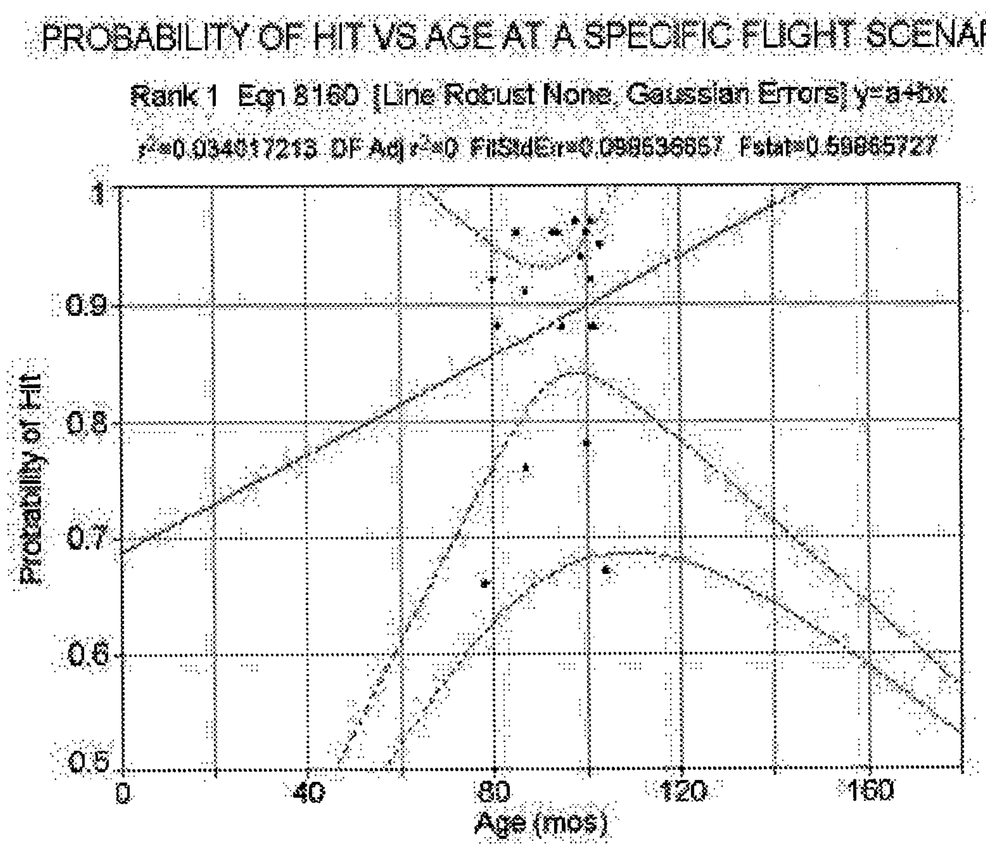
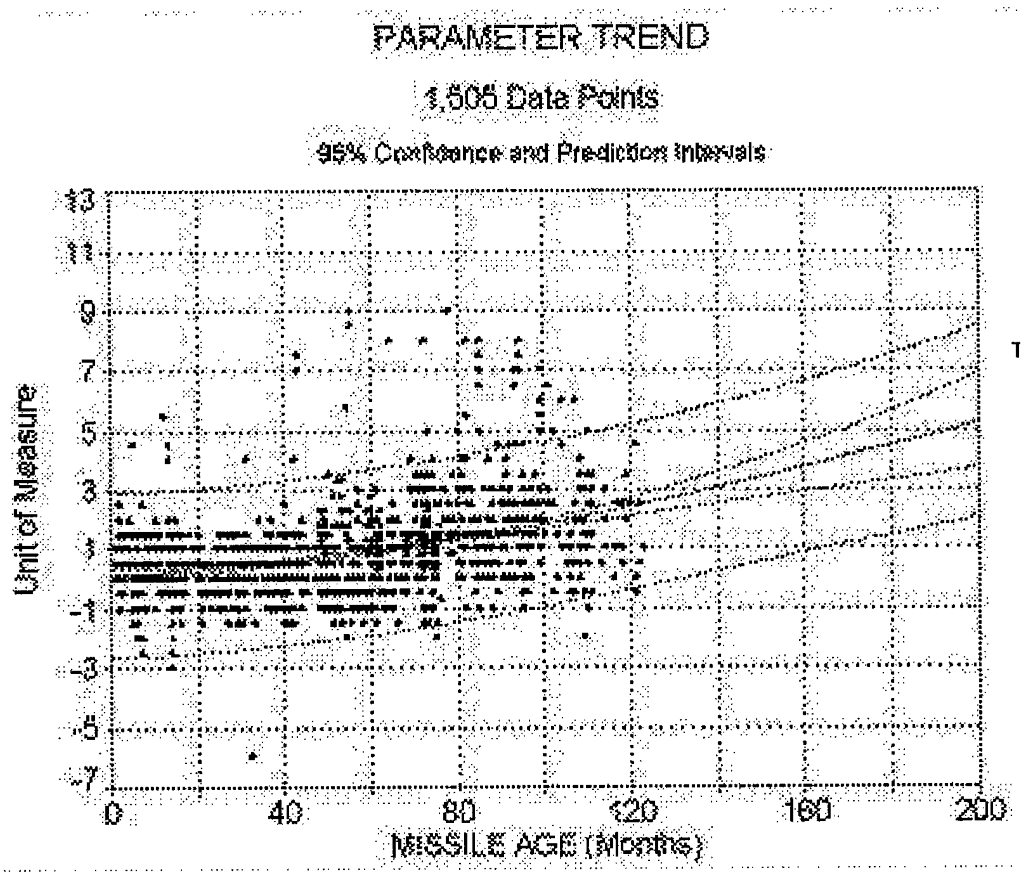


Figure 2. Example of probability of hit based trend analysis. (Note: Data not to be construed as actual)

approach for application of the simulation. The new methodology identified is simply an extension of the current trend analysis process into simulations. This method optimizes the available SRP data, and eliminates the shortfalls of the traditional method. Utilizing the HELLFIRE SRP database, thousands of readings taken on many of the electronic parameters is plotted versus age for trend analysis. The large number of readings provide trend analyses of high confidence. Figure 3 provides an example of one of these trend analyses for three to ten year old missiles. The fitted line is projected out as a prediction of the performance of this parameter in the future. This analysis is performed on hundreds of individual parameters. Other than being able to now utilize the significant amount of data being entered into the SRP database, this is the same as the traditional method of SRP analysis. The next step is the new approach. Using figure

3 as an example, we extract a predicted mean and distribution for this parameter at 15 years. This same "extraction" can be performed from all of



the individual parameters trend analyses. The extracted parameter means and distributions are simultaneously input to the simulation, "building-up" the predicted model for a 15 year-old missile. This model can be run through 5000 run-sets for each of the standard 20 flight scenarios. This effort utilizes all available test data, identifies actual missile performance impacts of all parameter trends combined, and predicts future performance.

LIMITATIONS OF PERFORMANCE PREDICTION

Utilizing this new method does not eliminate limitations associated to the traditional process of performing degradation trend analyses of individual parameters. That is, the mathematics of plotting the data and applying a best-fit line for predictions is the same. This process is subject to difficulties in determining that trends are actual age degradation, and not associated to some change in test methodology, sample population, etc. Additionally, this

process does not identify the mechanism behind the trend, which should be determined in order to validate the prediction.

There are also some parameters for which trends or failures cannot be analyzed well using the HELLFIRE simulation. Generally this includes all of the "one-shot" components (thermal battery, gyroscopes, accumulator/ regulator, rocket motor, warhead, and S&A). Some of these devices have no/limited modeling fidelity in the simulation. For example, in the case of the thermal batteries, there was no modeling in the original simulation. A voltage level at which the missile fails hard was identified in laboratory testing. The improvement to the model was basically to create a "truncation" point for a simulated flight when the battery falls below that minimum level. This is a crude model since the power requirements and usage can be affected significantly by a variety of factors. Some of the one-shot components are treated in the simulation as go/no-go. For example, either the fuze arms or it doesn't. All of these one-shot items still require traditional SRP analyses.

There is not a developed methodology for the determination of distributions to be applied to the predicted values. Look at the point where the 15-year predicted value was extracted from the fitted line in figure 3. We could utilize the prediction lines at that age to determine standard deviation for a normal distribution around that predicted mean point. Although the use of prediction lines beyond the data set is mathematically inappropriate, the expanding lines do represent some level of increasing uncertainty in the prediction. Another method is to utilize the current distribution determined for each parameter and apply that distribution around the extracted value. Neither of these methods is considered to be the best solution and there is room for further development in this area.

CONSIDERATIONS FOR PROGRAMMING AND SYSTEM DESIGN

One result of the activities described herein is increased knowledge of how the simulations model should be designed for life cycle use. The fidelity of the model is critical. Subsystems should be modeled to their subcomponents, and the subcomponents to each independent output. This is obviously difficult early in the design, and requires close integration of the simulations and engineering activities. Continuous changes to the model will occur as the design is solidified. Additionally, the simulation should be revisited after full rate production to verify that means and distributions are representative of actual hardware being produced.

Alternatively, specific considerations should be taken into account for the design of the hardware. The methodology becomes more powerful if a greater number of performance affecting parameters can be non-destructively measured and input to the simulation model. Thus, the hardware should be designed for testability. The extensive use of missile hardware-in-the-loop (HWIL) testing in modern systems has indirectly resulted in significant contributions to this objective. HWIL testability requires access to critical data streams, and high fidelity simulation models.

SUMMARY

Depending on the fidelity of the original simulations model, the process described herein can be utilized to effectively develop the model for life cycle uses. However, the best case would be to plan for, and develop the model for this application early in program development. Proper development of the model for this use requires the teamwork of personnel from a variety of disciplines, to include simulations, reliability, systems, and test. Combining traditional SRP trend analysis with simulations provides a new capability to predict future performance, and has significant potential for growth into other life cycle applications.